On the effect of Magnetospheric Shielding on the Lunar Hydrogen Distribution

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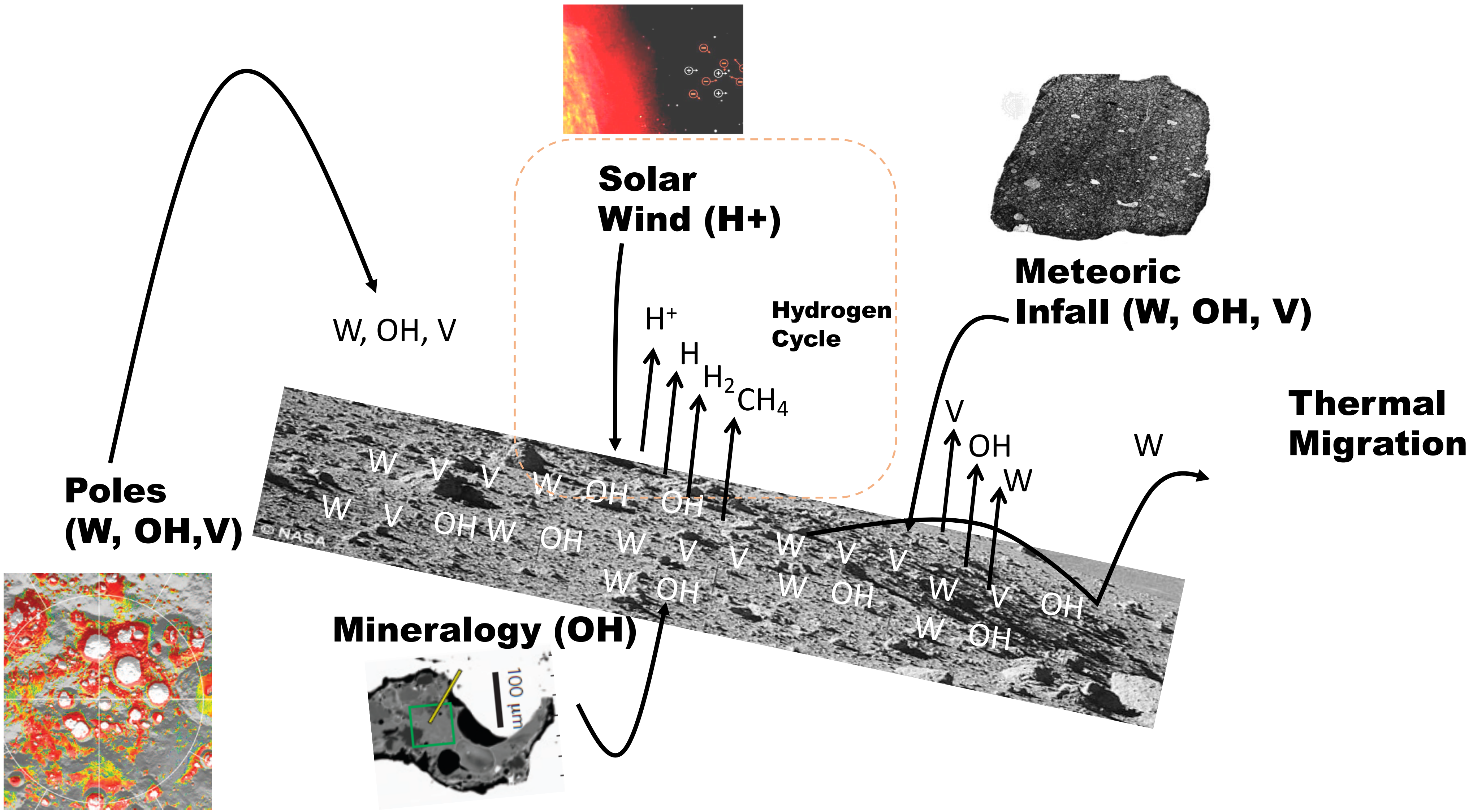
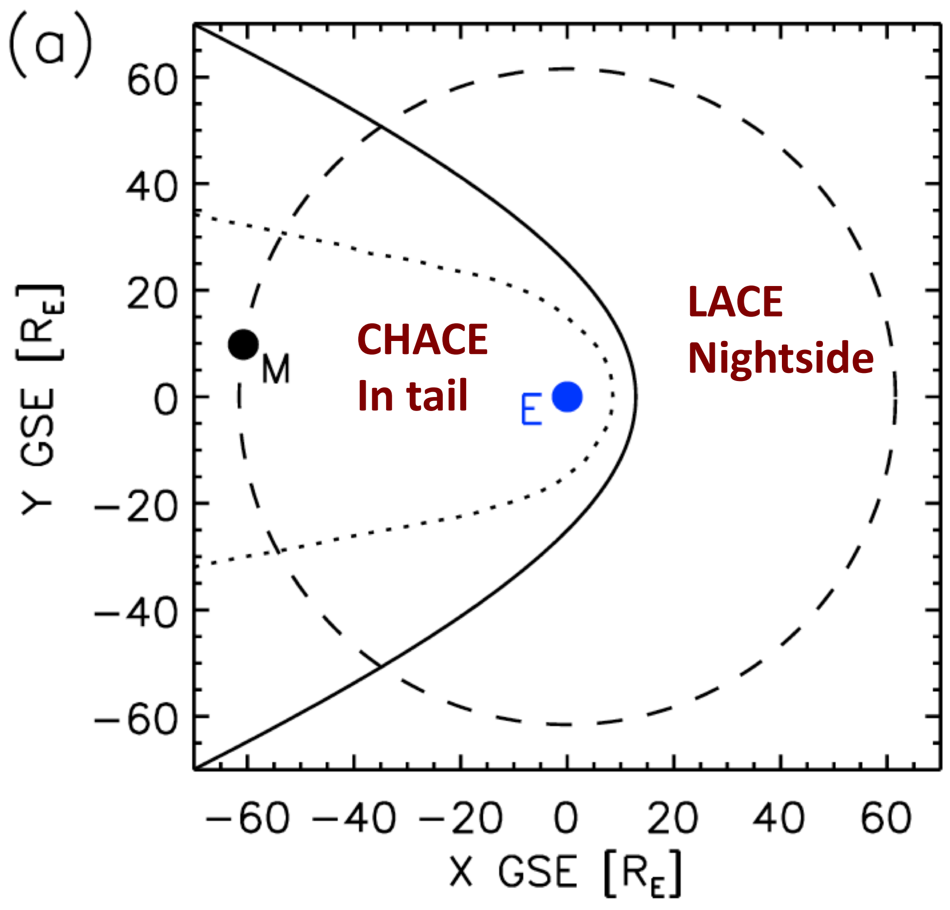
Understanding the Lunar Hydrogen Cycle

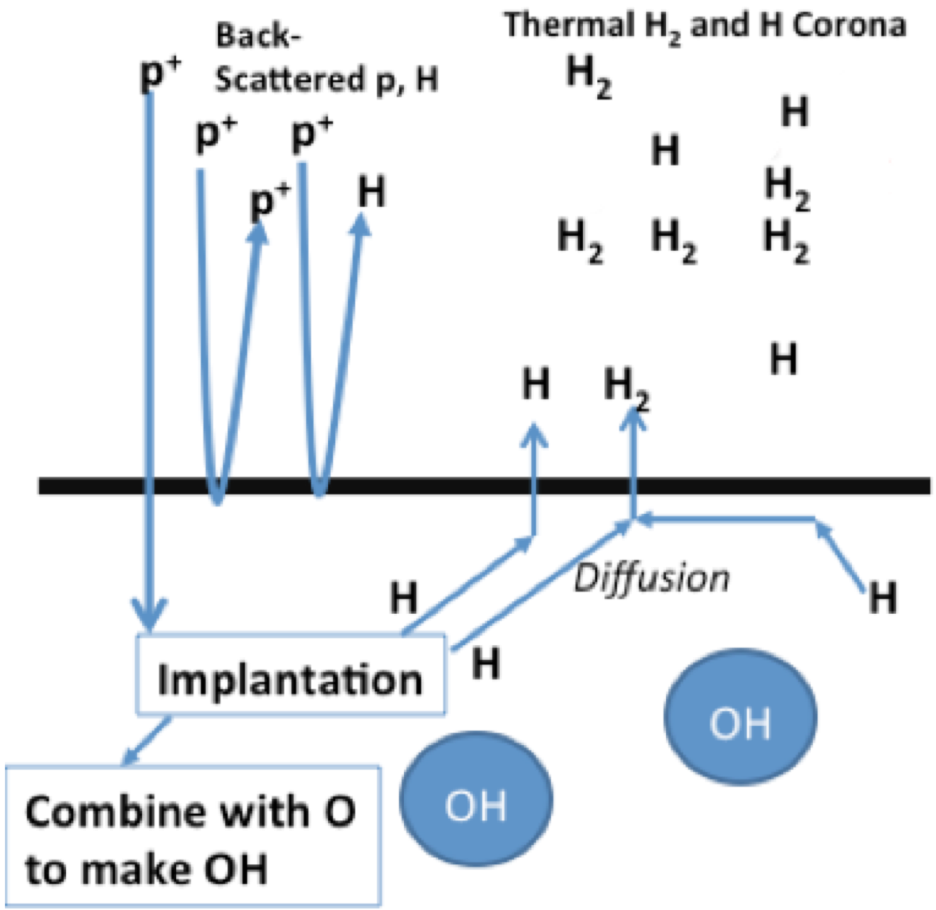


Observations of the H Cycle

- ARTEMIS Charged Particle Detect.
  - *5 years of ion data (Poppe et al. 2017 JGR)*
- CHACE Mass Spec.
  - *H_2 = 500 – 800 cc in tail (Thampi et al. 2015 PSS)*
- LAMP UV Spec.
  - *H_2 = 1200±400 cc at T = 120K (Stern et al. 2013 Icarus)*
- LACE Surface Mass Spec.
  - *H_2 = 6.5e4 cc (Upper Limit), SZA ~ (-136^0, 168^0, -89^0)*
  - *(Hoffman et al. 1973. Proc. Lunar Sci. Conf. 4, 2865)*
- M^3 IR Observations
  - *Rel. abs. ~0.31 (in tail) & ~0.35 (out tail), 0-10 lat.*
  - *ESPAT ~0.25 (in tail) & ~0.4 (out tail), -55 lat.*
  - *(Cho et al. 2018 JGR; Li et al. 2018 LPSC)*



Solar Wind Implantation and Diffusion



- Diffusion characterized by surface T & density of defect sites (Starukhina, 2006, 2012)
  - $\tau_D = h^2 \exp(E/T)/D_0$
- Distribution of activation energies (Farrell et al. 2015/2017)
  - $F(E) \sim \exp(-(E - E_a)^2/E_W^2)$
  - E_a – peak energy, E_w – width of distribution

T(K)	$E_{V\&CB}$ =1.0 eV	$E_{Int\&GB}$ = 0.5 eV
180	>> Gyrs	12 days
280	31 decades	10 seconds

We examine the H -> OH -> H2 pathway in surface and exosphere

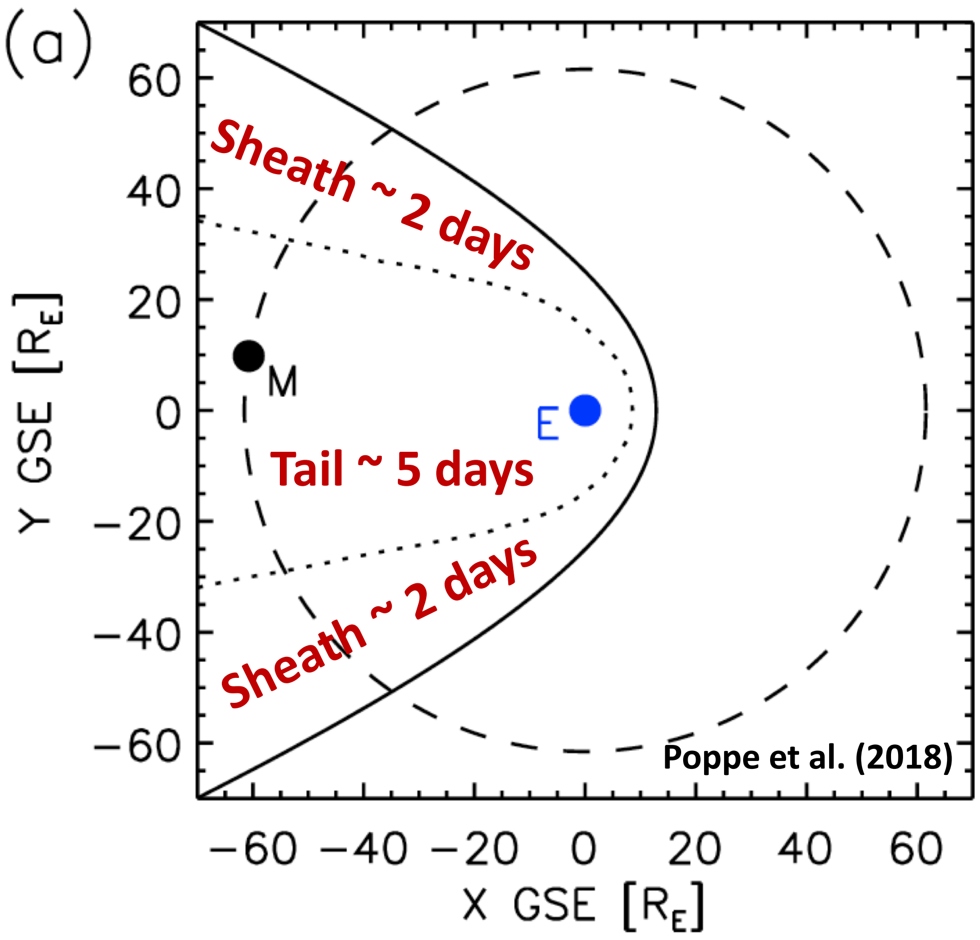
Simulation Details

- **Track dynamic steady state of H surface density and exosphere**

- **Source:** Proton Flux
- **Losses:** Thermal Escape & Photodestruction

Monte Carlo Model

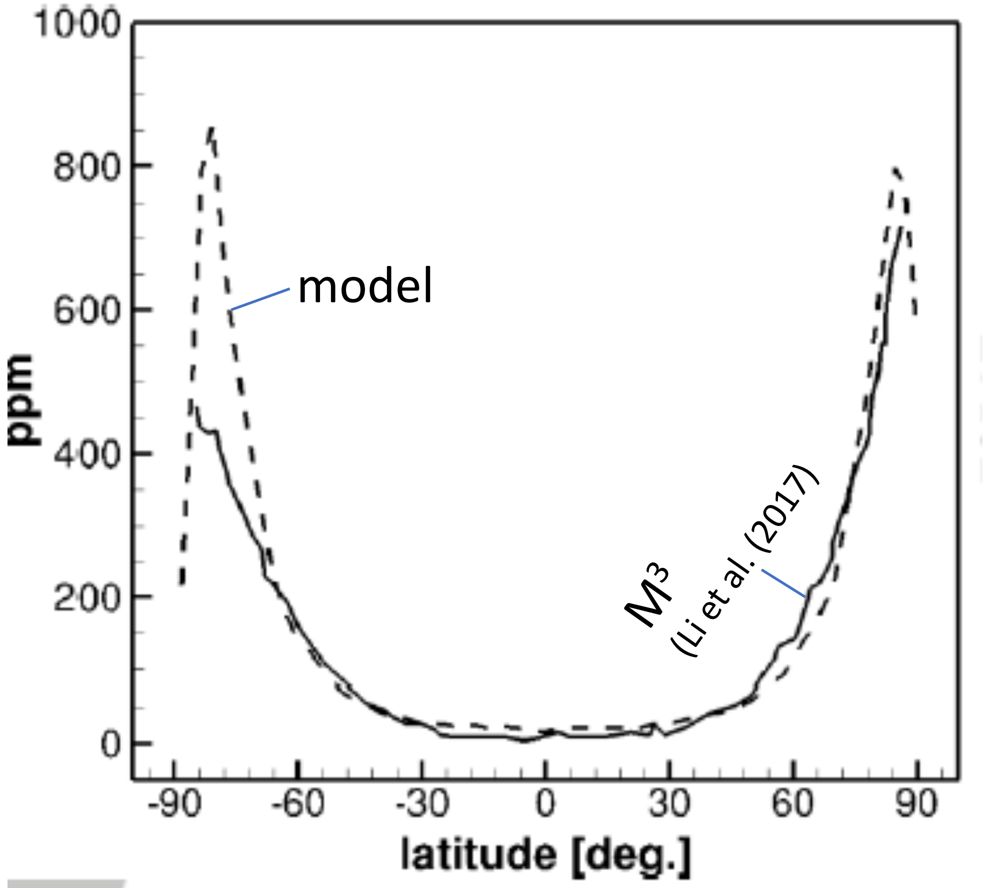
- Implantation Depth: *f*(Z)
- Incident Ion Energy: *f*(E_i)
- Diffusive Lifetime: *f*(E)
- Thermal desorption: *f*(v)
- Photo-destruction Lifetime



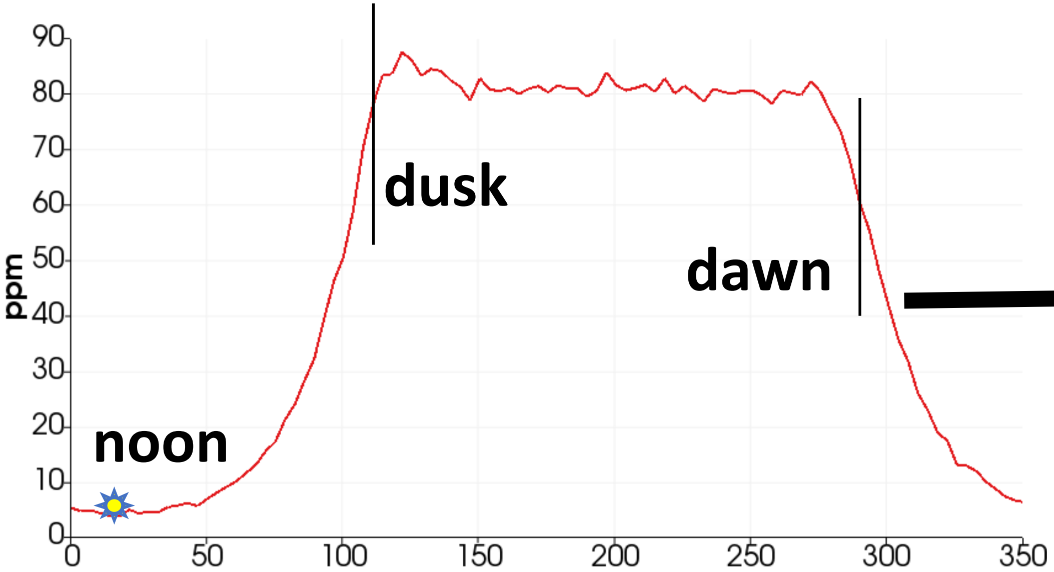
Previous Work

- Mean M^3 surface concentration reproduced with:
  - **(D_0 = 10^{-12} m^2/s, E_a ~ 0.5 eV, E_w ~ 0.078 eV)**
- E_a ~ > 0.7eV too much H retention
- E_a ~ < 0.3eV too little H retention

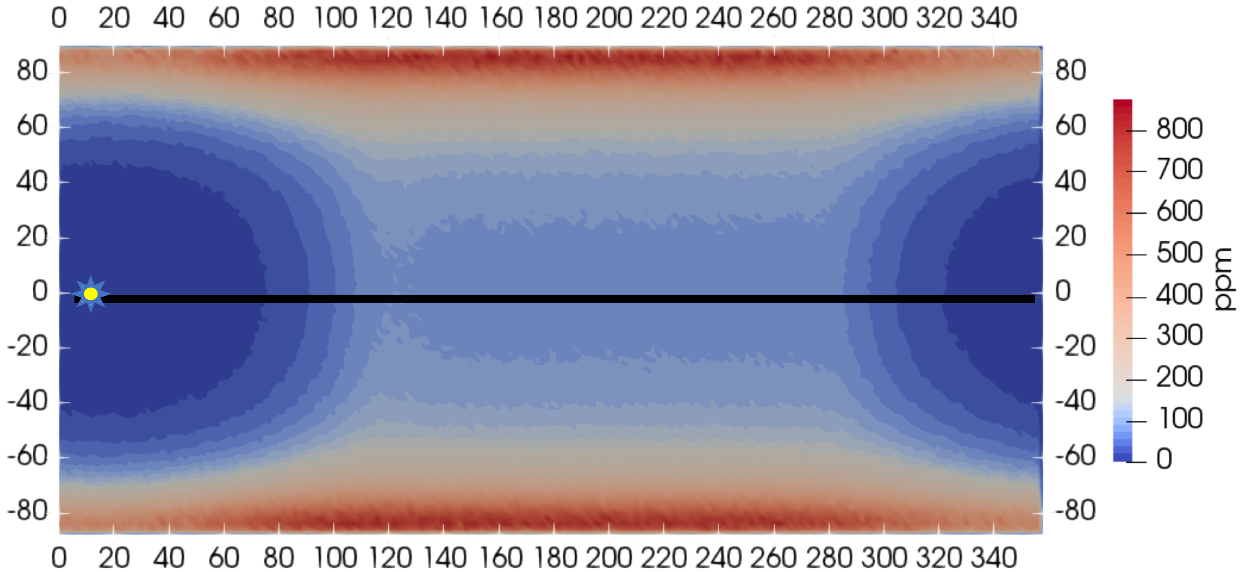
Farrell et al. (2017), Tucker et al. (2019)



Surface Concentration at Full Moon

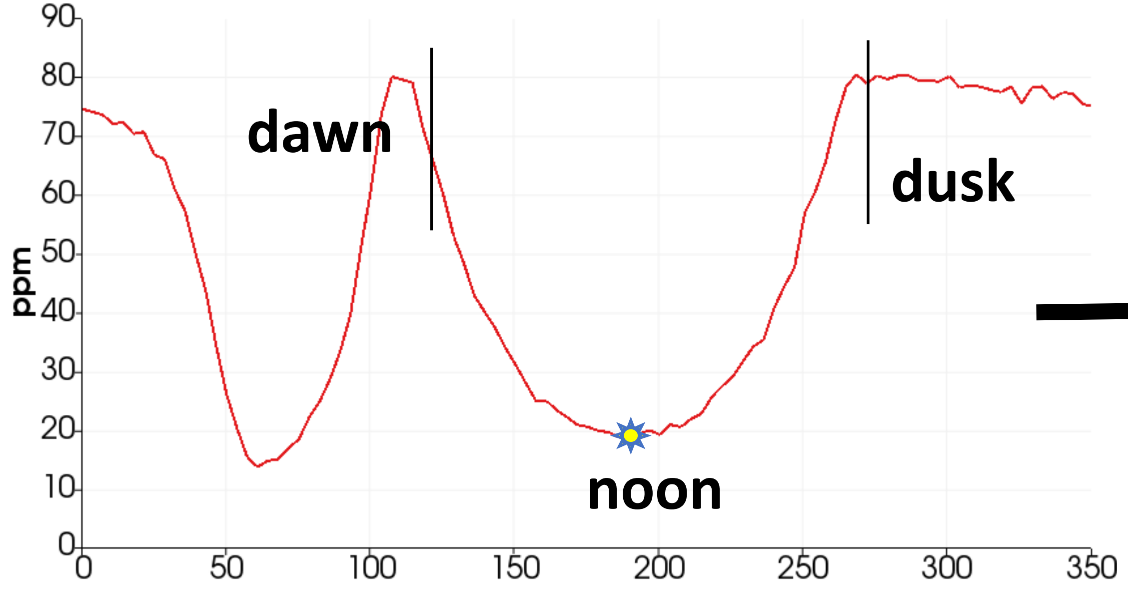


Surface Concentration at 0 latitude

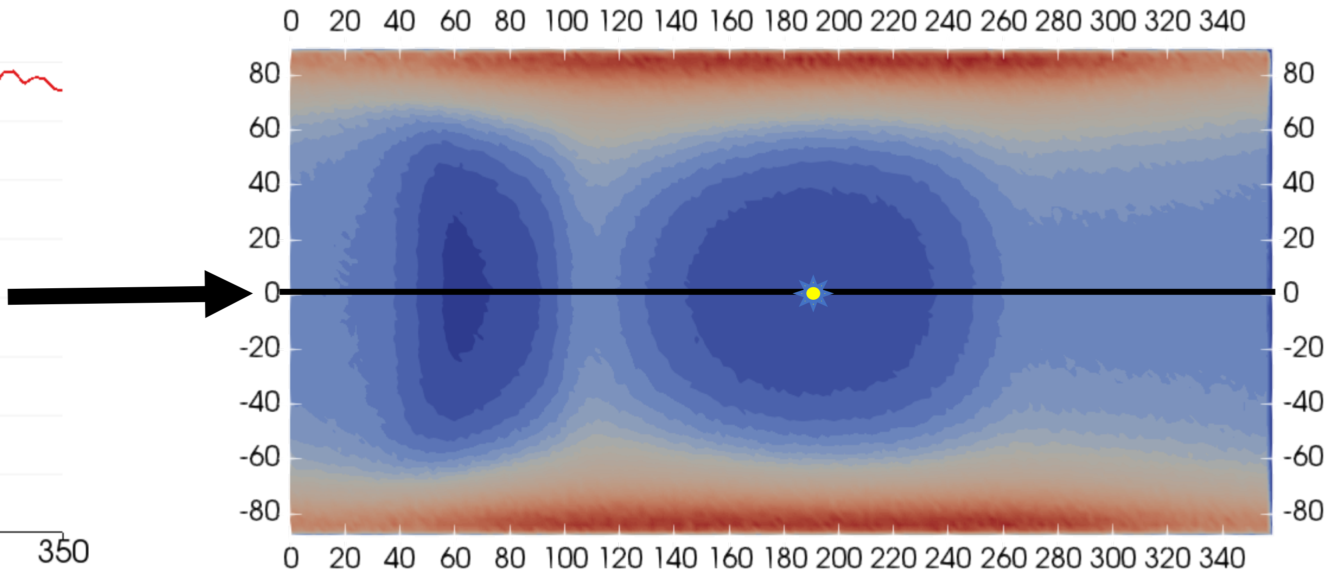


Snapshot of Surface Concentration

Surface Concentration at New Moon

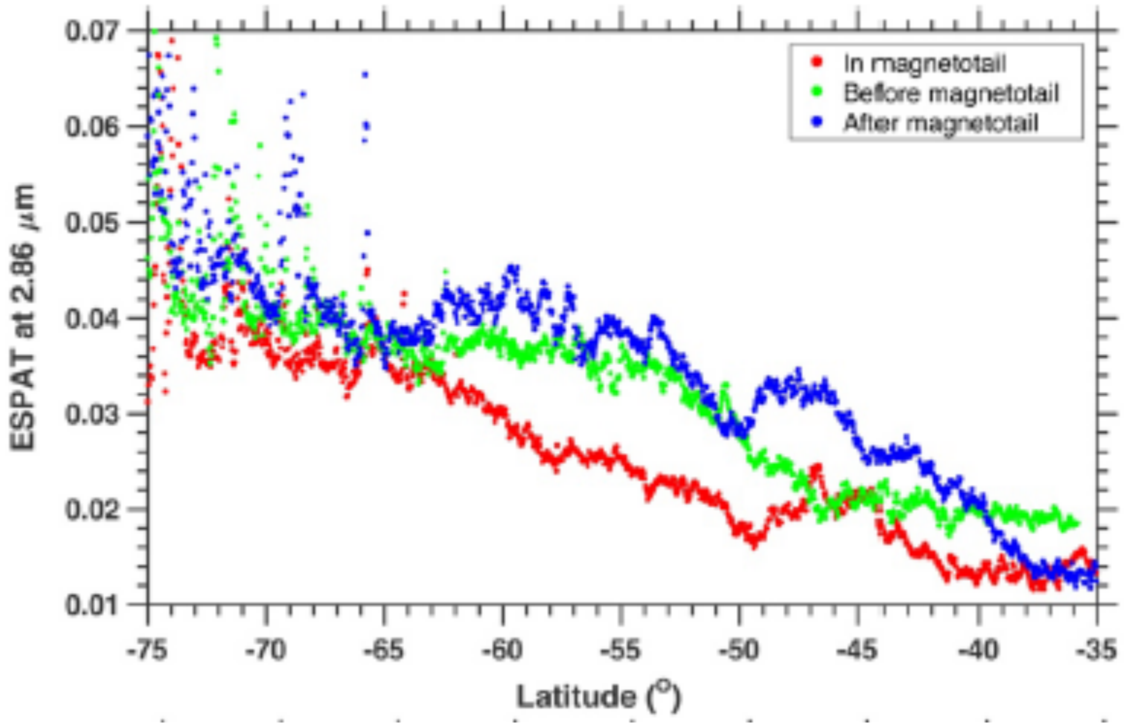


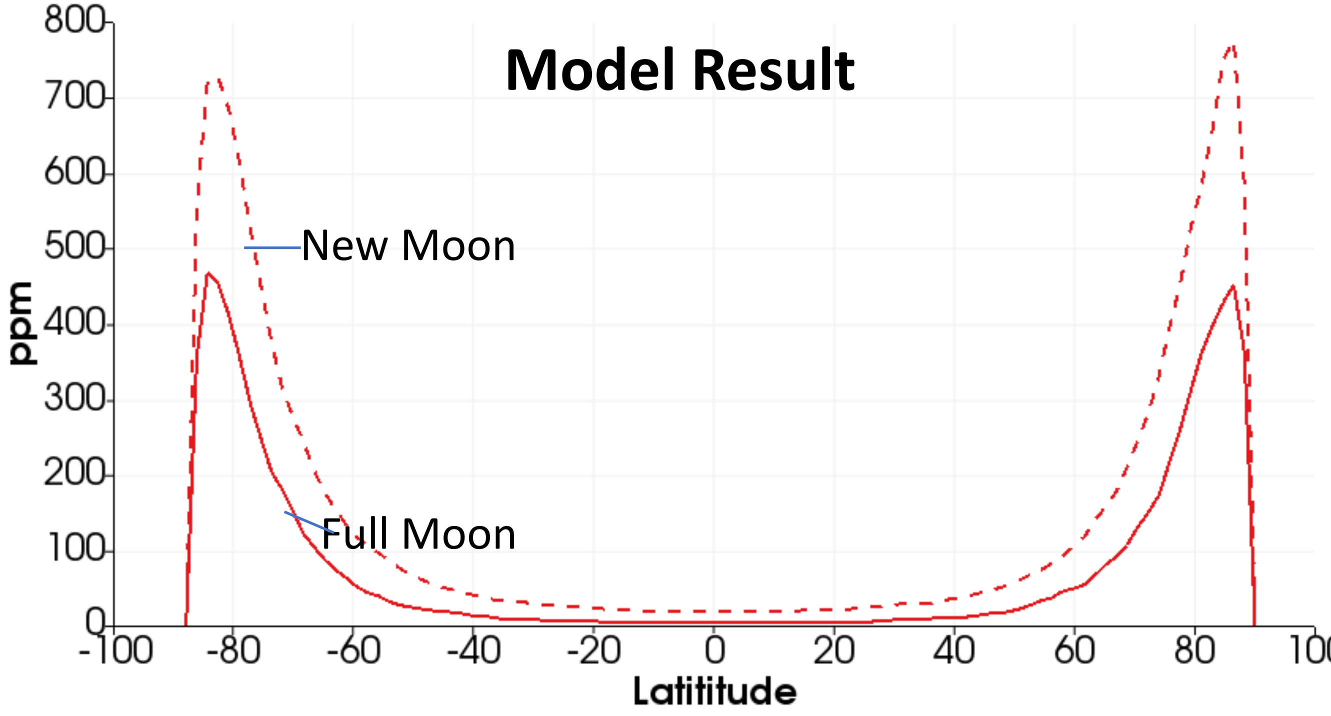
Surface Concentration at 0 latitude



Snapshot of Surface Concentration

Subsolar Concentration Full/New Moon

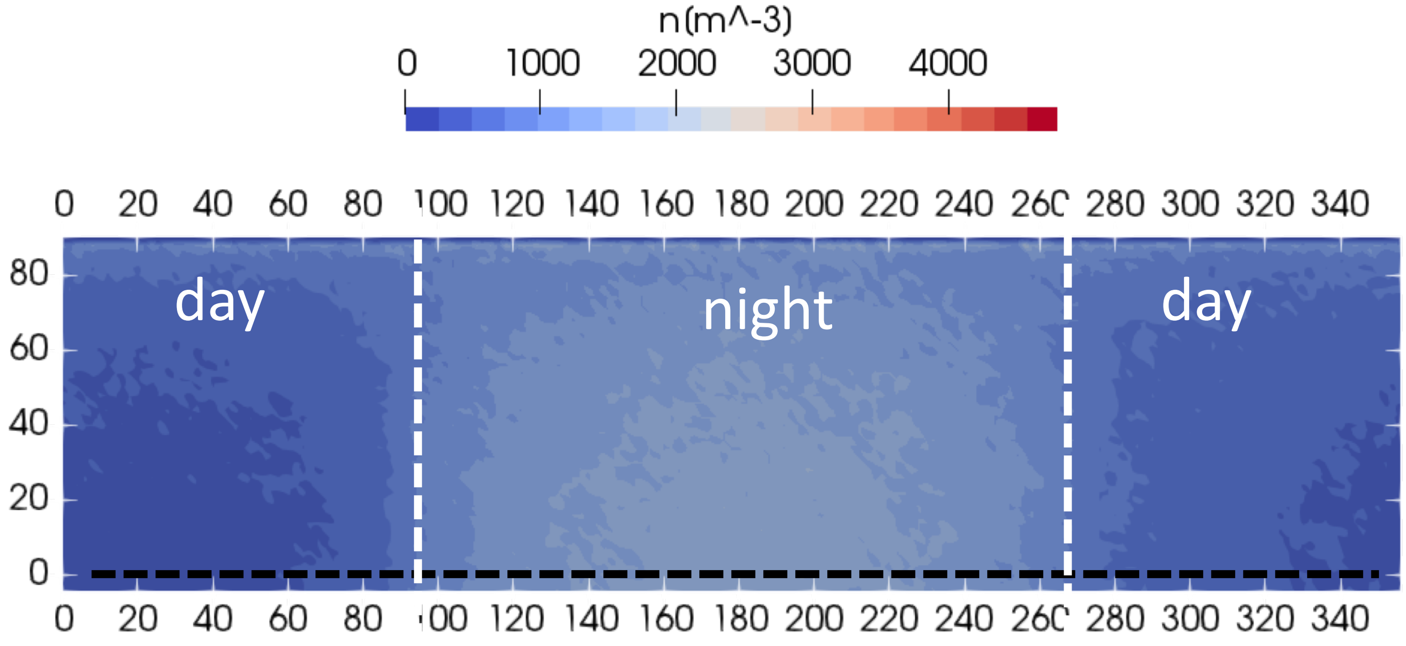




- LPSC M^3 spectra in and out of tail: Li et al. (2018)
- Model does not account librations or fluctuations of tail due to Solar Events

Exosphere Surface Number Density (H_2)

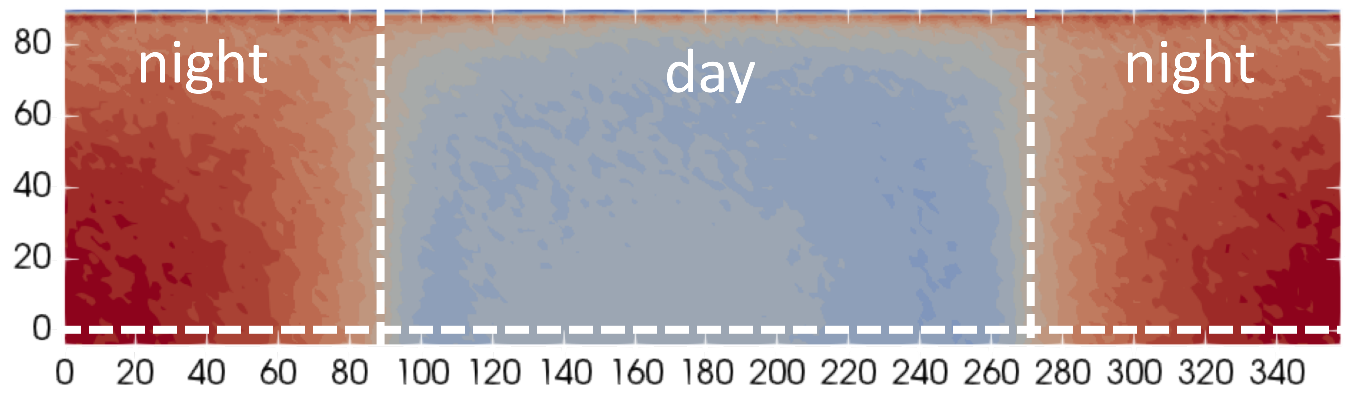
Distribution during full moon

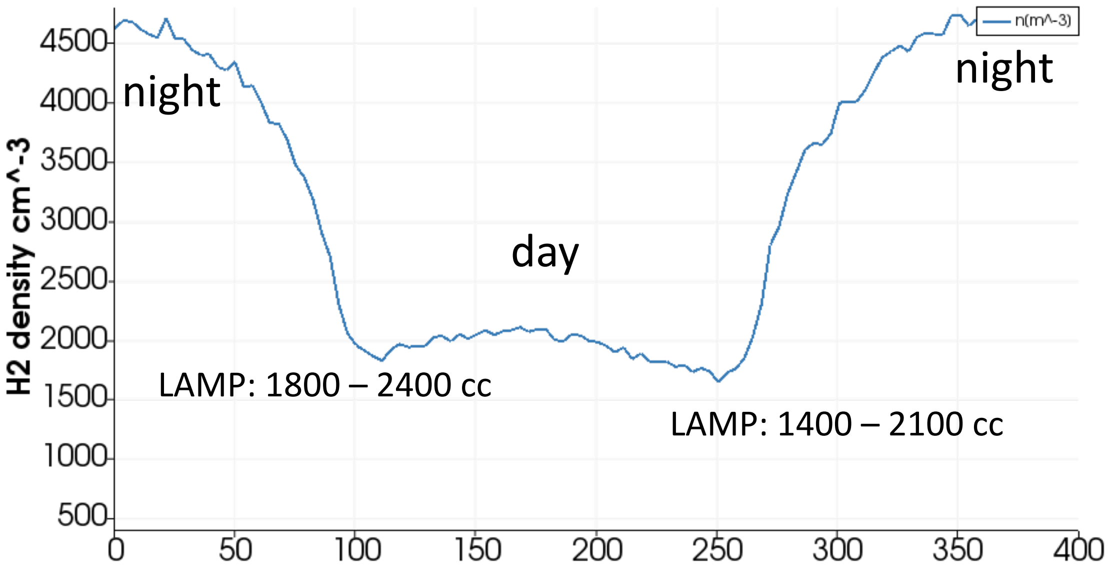


- **LAMP analyses of H_2 in tail ~1000 cc (*Cook et al. LPSC 2016*)**
- ***Subsolar density ~ 400cc***

Exosphere Surface Number Density H_2

Distribution during new moon

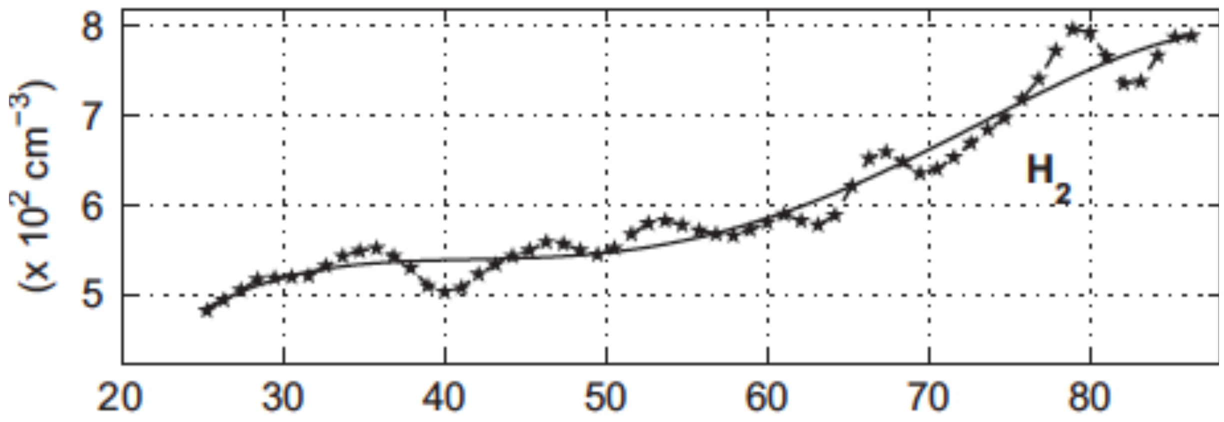




- **Consistent with dusk/dawn asymmetry reported in Cook et al. (2013)**
- **Subsolar density ~ 2000 cc, 80% larger than when in tail**

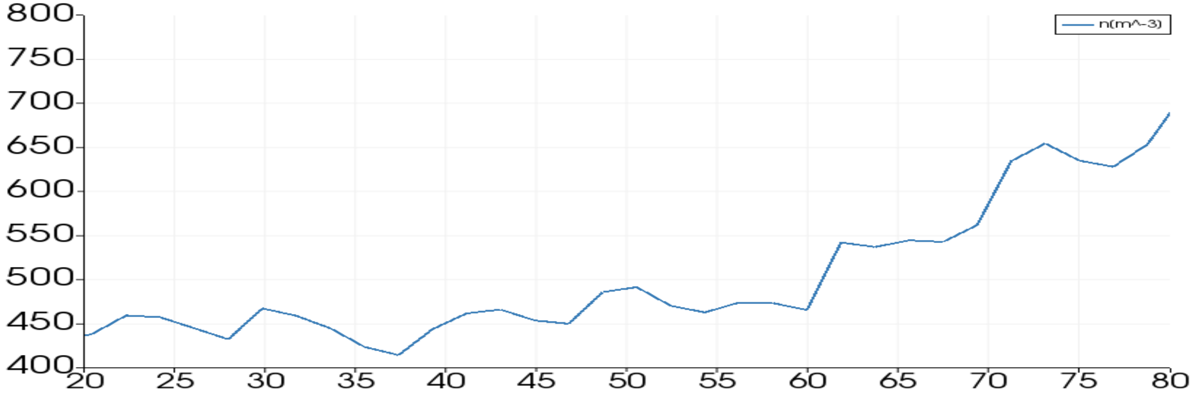
CHACE Measurements of H_2 in Magnetotail

CHACE



latitude

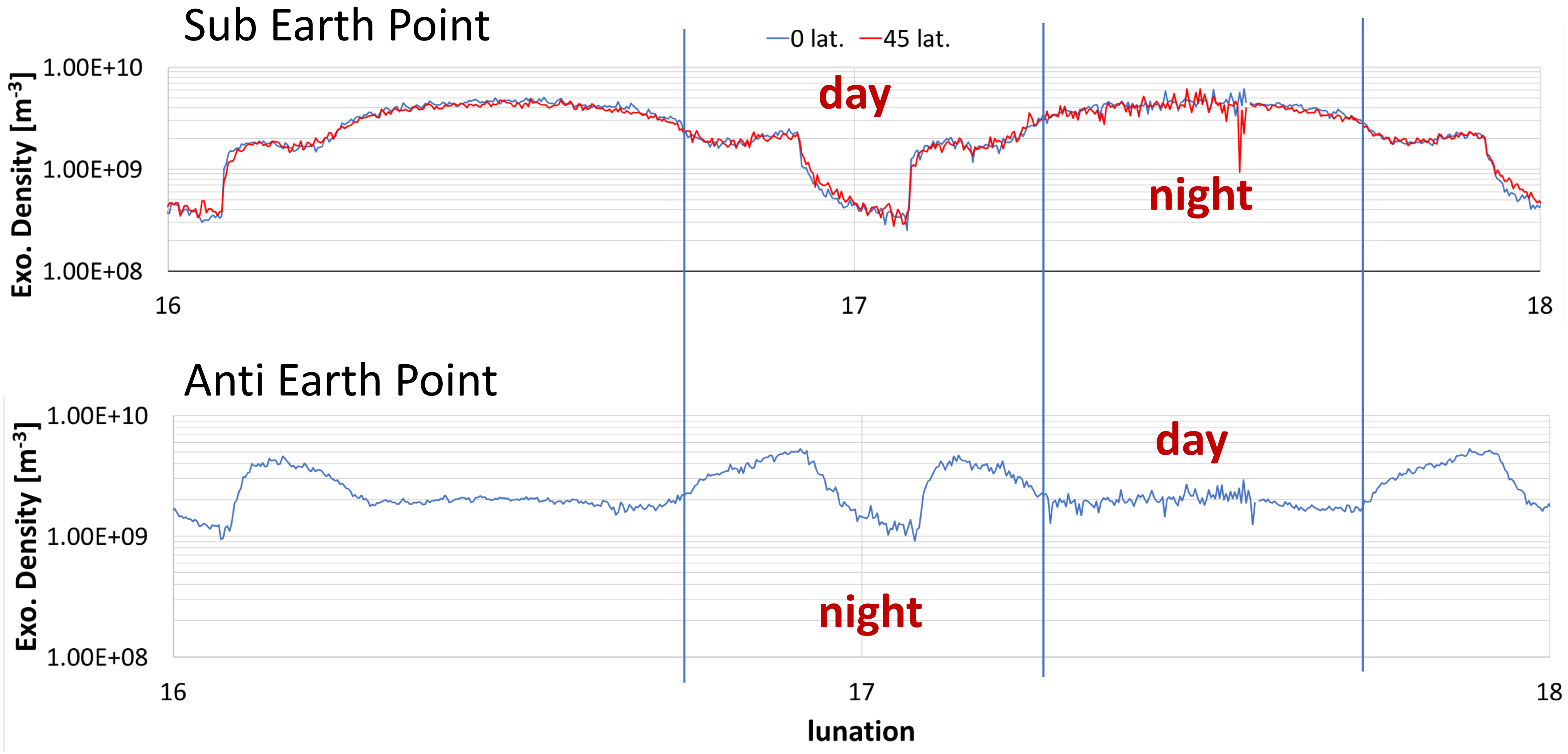
Model



latitude

- **Dayside Distribution consistent with model calculation**
- **H_2 Lifetime against escape on order of a couple hours**

Change in Local Exosphere Density H_2 over lunation



Independent Observations of H_2 Seem consistent

- Thampi et al. (2015)……. 'our estimates are significantly lower than the upper limits for dawn hours (2100 – 2400 cc), reported by Cook Jason et al. (2013)'.
- Expect Changes in SW sources with lifetimes < ~ 5 days: thermal escape H_2, He
- Not expected to see changes in species like Ne, Ar

LAMP Observations

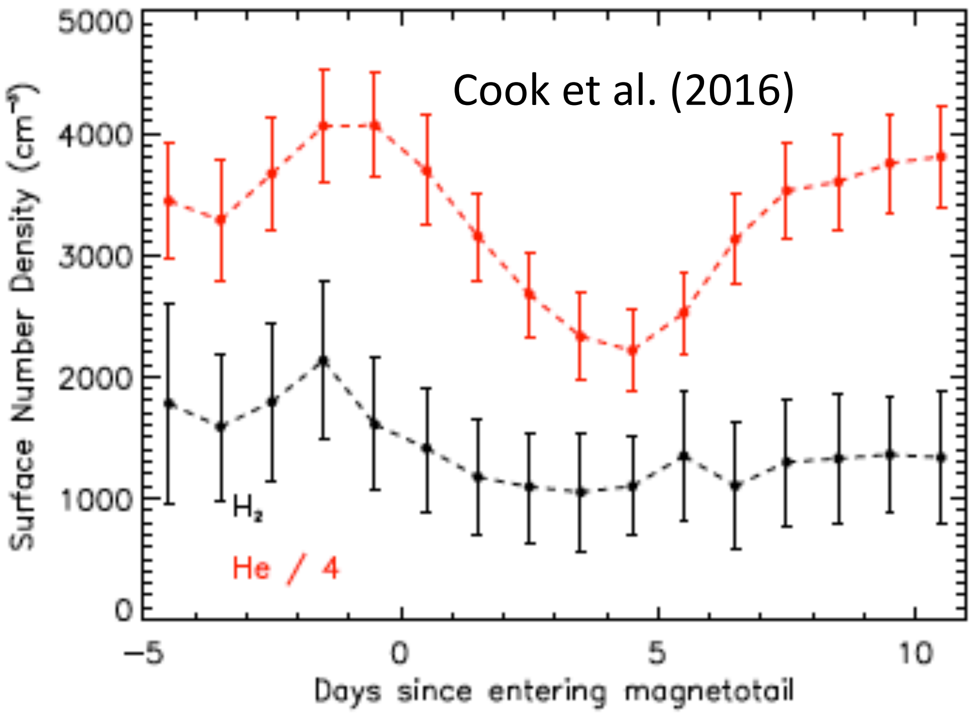


Figure 3: He and H_2 surface number density as a function of time as the Moon passes through the Earth's magnetotail. The data are averaged over 53 months.

Summary

- Connection between surface volatiles and exosphere content crucial to understand volatile cycles
- Local In Situ measurements over a Lunation can provide insight on H_2O vs. OH and dynamics controlling distribution
- At subsolar point surface concentration 20 ppm (in tail), 2 ppm (out of tail), and H2 exosphere order of magnitude decrease in tail.
- Diffusion of H in irradiated silica not well constrained (D_0, E_a, E_w) requires experiments and theoretical studies

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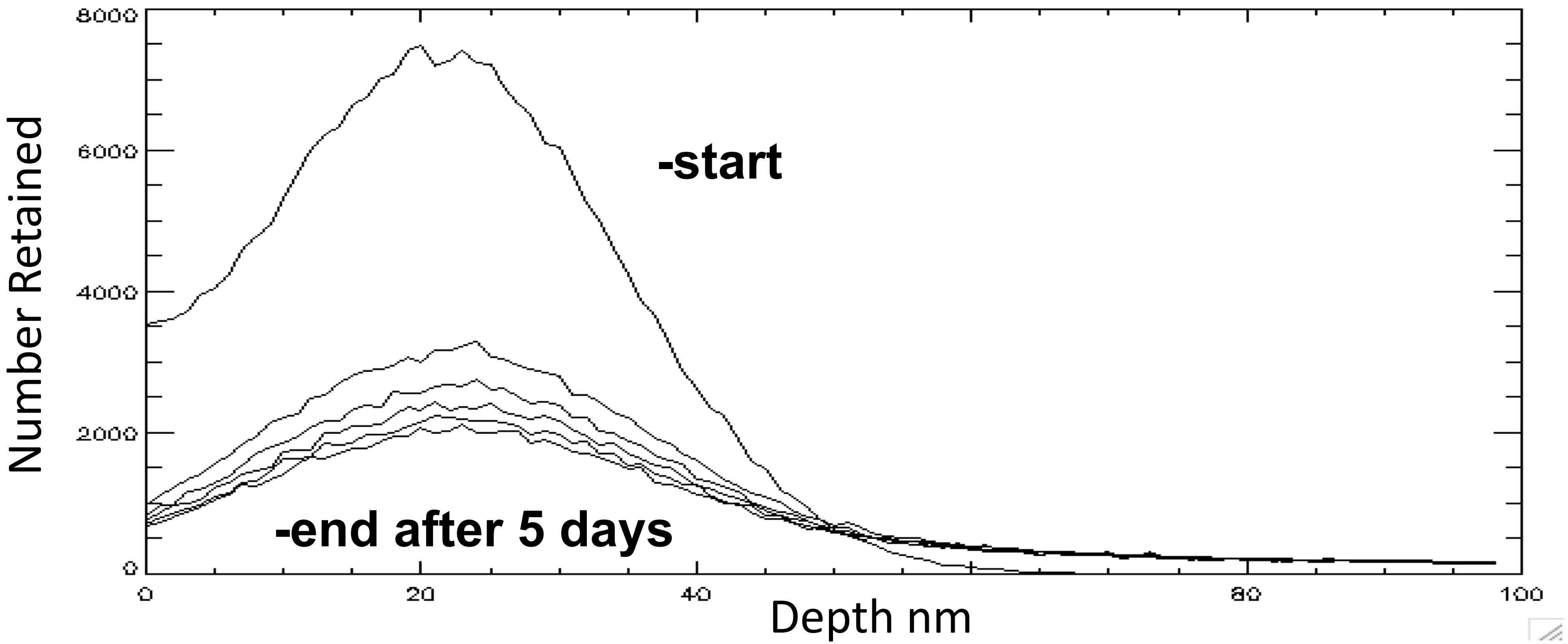
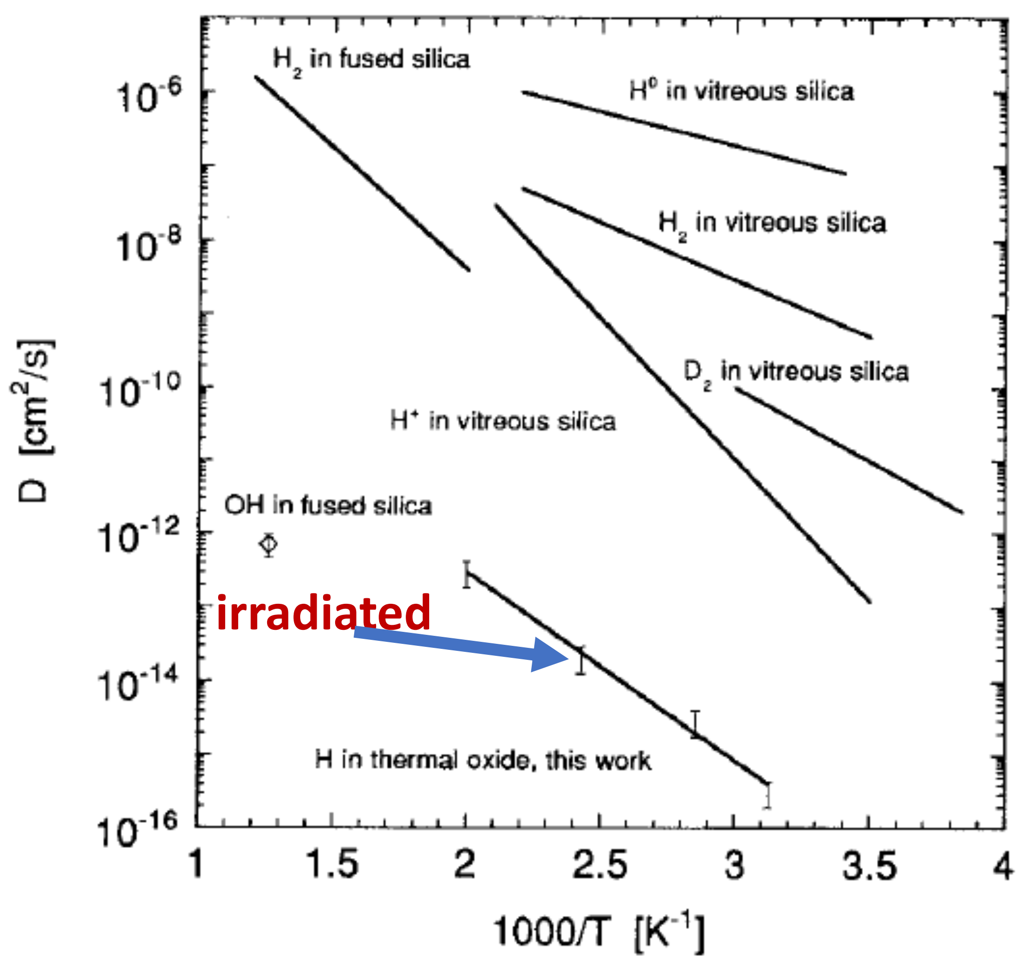
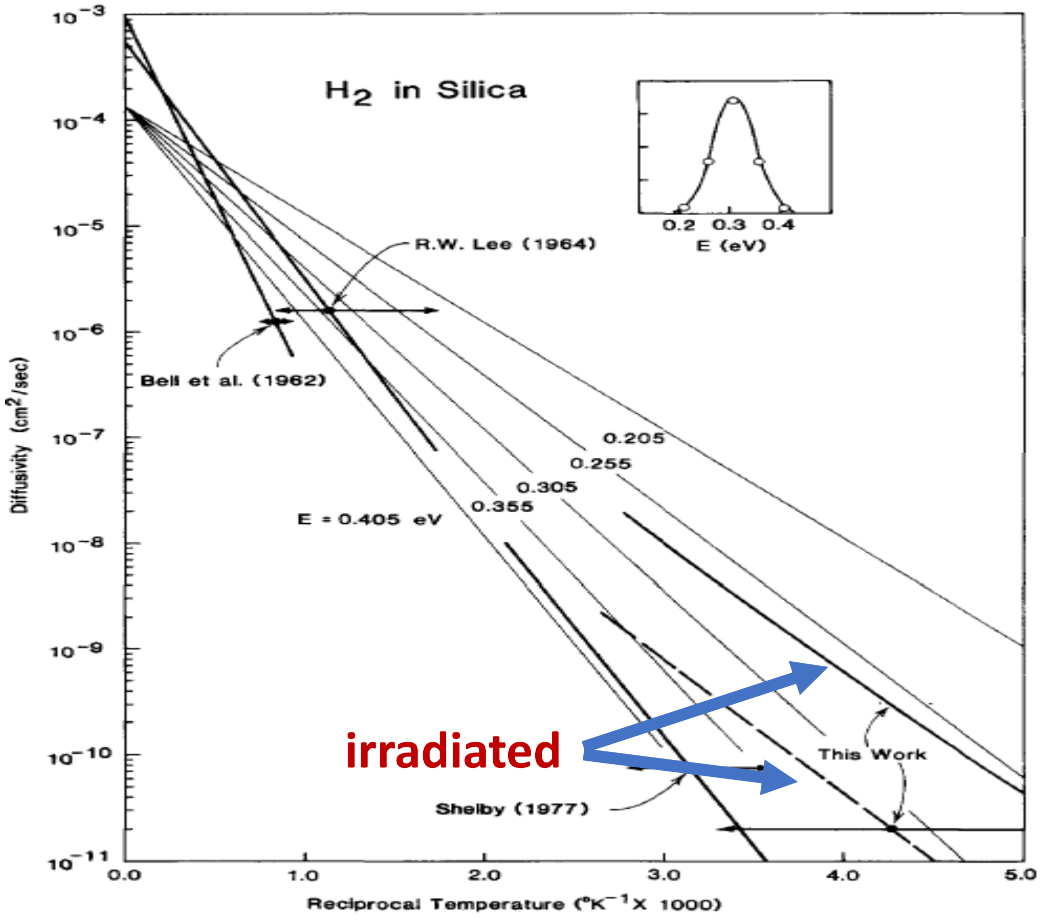
Loss of hydrogen in the tail



Implanted H atoms with activation energies > 0.5 eV contribute to the long term surface concentration

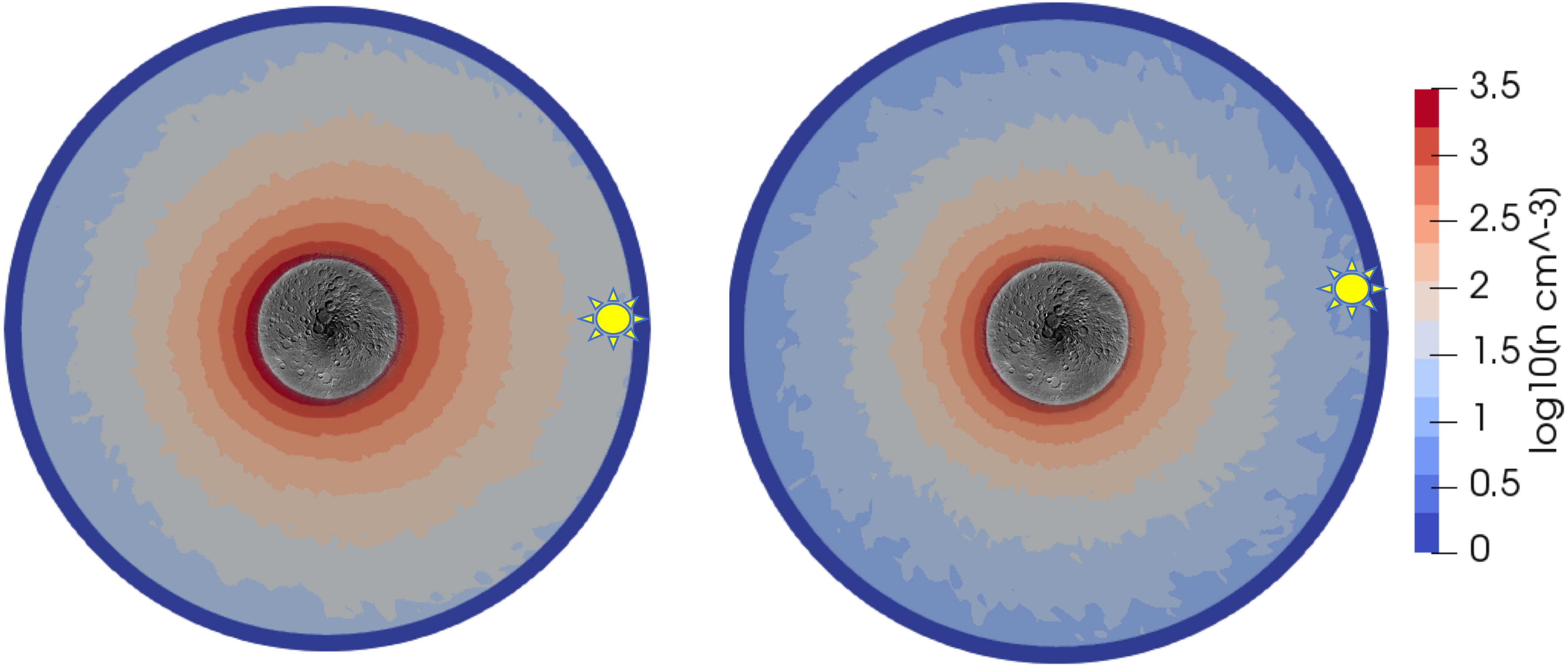
Hydrogen Diffusion in Silica affected by Defect Abundance





Diffusion Prefactor $\mathbf{D_0 \sim 10^{-9} - 10^{-12}\ m^2/s}$: Fink et al. (1995) & Griscom et al. (1984)
Activation Energies $\mathbf{E_a \sim 0.2 - 0.5\ eV}$: Fink et al. (1995), Griscom et al. (1984), Devine (1985)

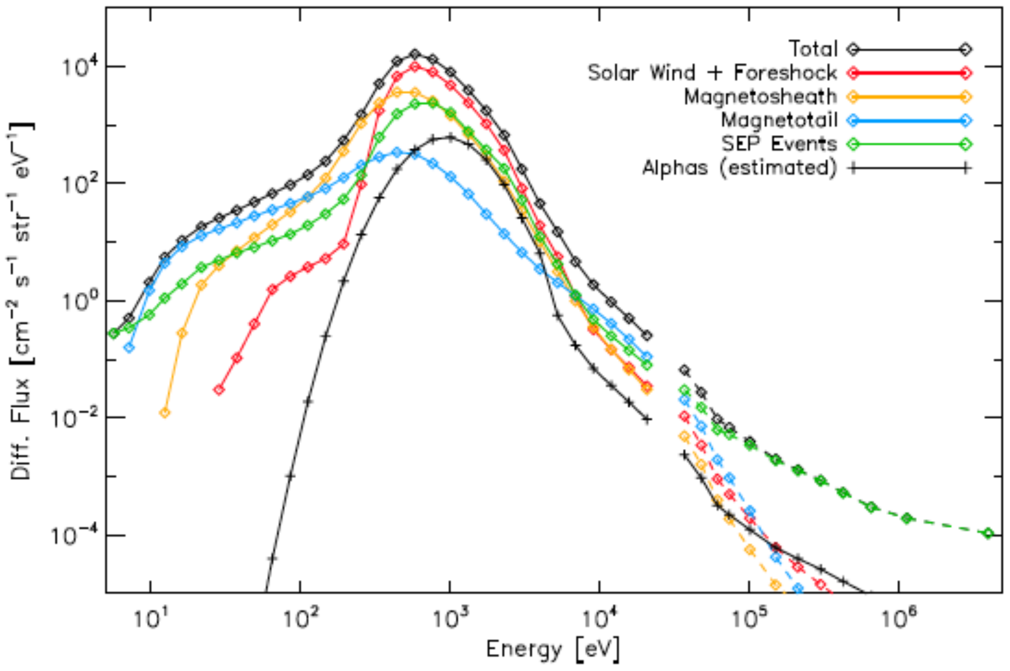
Global H_2 Density in Equatorial Slice

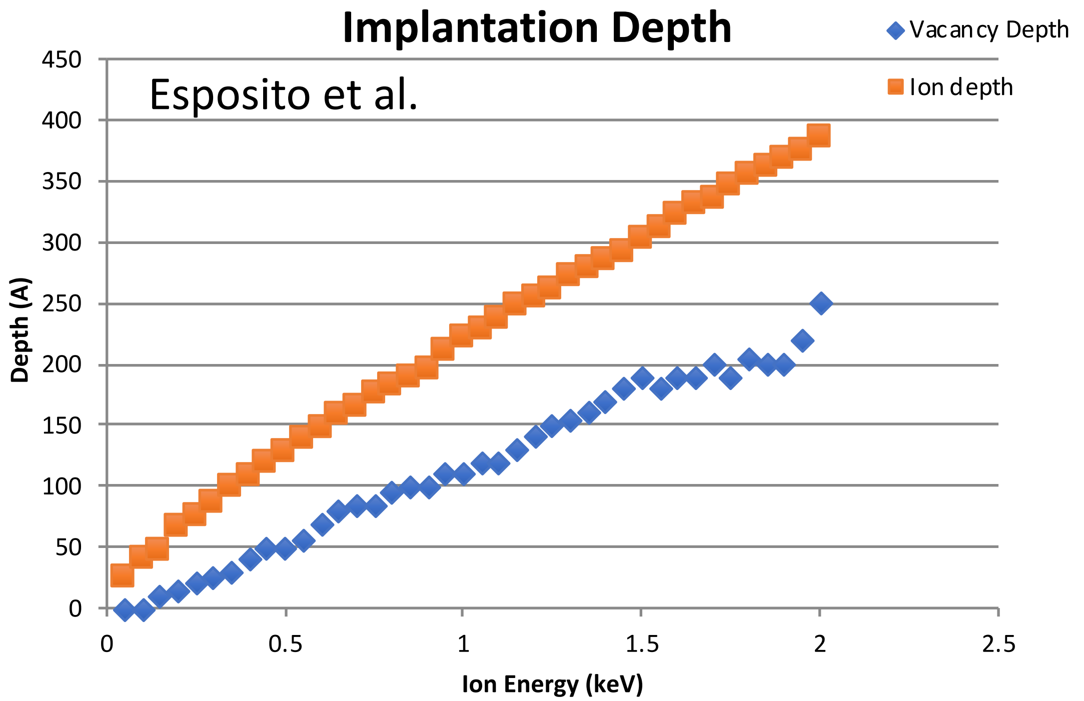


New Moon

Full Moon

Implantation Depth vs. Incident Ion Energy





Poppe et al. (2018) using ARTEMIS data characterizes incident flux on surface:

Mean Sheath Flux = 2.4E12 $cm^{-2}\ s^{-1}$

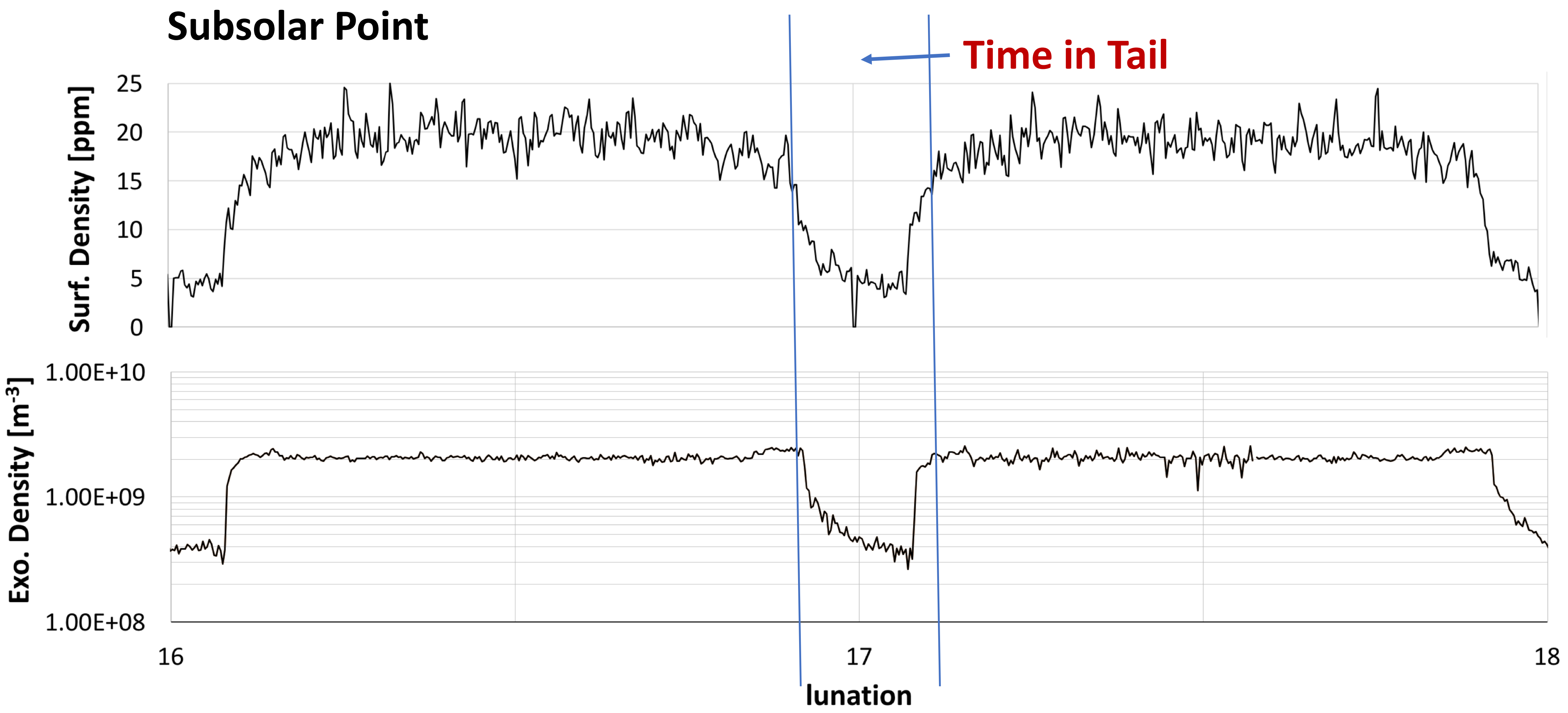
Mean Tail Flux = 2.2E11 $cm^{-2}\ s^{-1}$

Mean SW Flux = 2E12 $cm^{-2}\ s^{-1}$

For each implanted proton

- Monte Carlo select incident energy
- Incident energy determines implantation depth
- Surface temperature & Monte Carlo selected activation energy determines lifetime

Surface OH and Exosphere H_2 over lunation



groups (a-SiO_2:OH). In particular, the reaction

$$\equiv \mathrm{Si{-}OH} \rightleftharpoons \equiv \mathrm{Si{-}O}^{\cdot} + \mathrm{H}^{\circ} \tag{1}$$

$$\equiv \mathrm{Si{-}O}^{\cdot} + \mathrm{H}_2 \xrightarrow{230\ \mathrm{K}} \equiv \mathrm{Si{-}OH} + \mathrm{H}^{\circ}, \tag{2}$$